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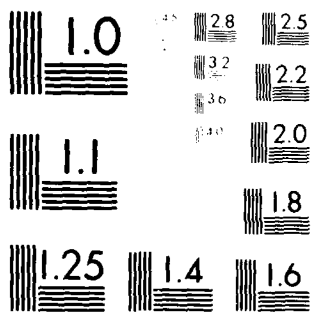

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COMPARISON OF ROUGHNESS RESISTANCE AS MEASURED BY FLAT PLATE AND ROTATING DISK

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

LEVEL II

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COMPARISON OF ROUGHNESS RESISTANCE

AS MEASURED BY FLAT PLATE AND ROTATING DISK

by

J. L. POWER & J. LIBBY

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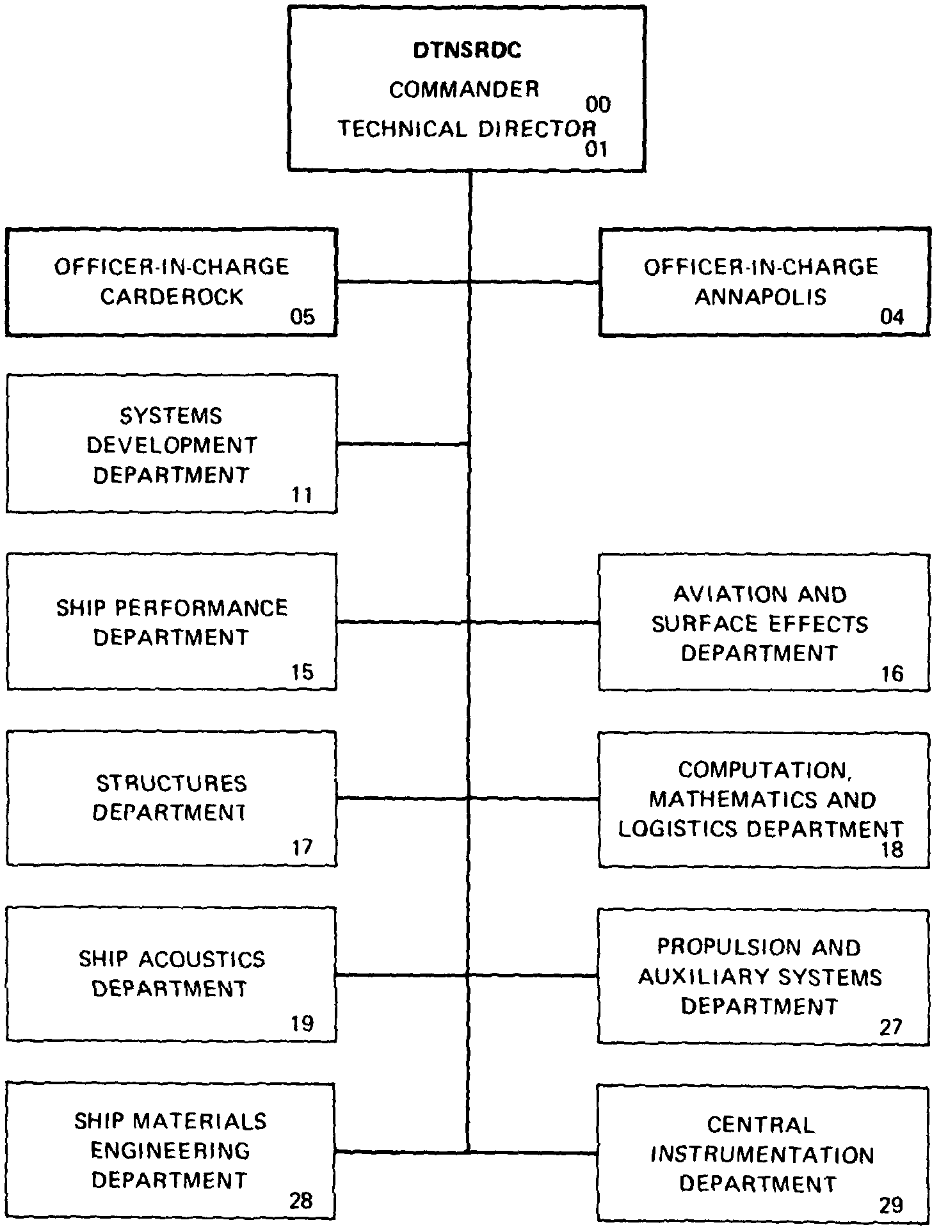

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The resistances of four surface roughnesses, formed by mixing paint with different grit sizes, have been investigated using a flat plate friction plane and a rotating disk apparatus. The purpose of the experiments was to compare the results obtained with the plate and disk. An attempt was made to keep the roughnesses between the plate and disks of each plate-disk set identical but only with partial success. The plate and disk results were compared by first determining the boundary-layer similarity-law-roughness characterization ΔB from the measured resistances of the plates and torques of the rotating

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disks. The values of ΔB were then used to estimate typical full-scale friction drags as predicted from the plate and disk data. Taking into account the differences between roughness height measurements taken on the plates and disks the compared extrapolated total friction drags for three of the four roughnesses were within 10 percent of each other. The results from the fourth and largest roughness show a larger disagreement between extrapolated values of total frictional drag. Except for Roughness 3, the discrepancies between measured changes in drag due to roughnesses on disks and plates were as much as 100 percent.

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ABSTRACT

The resistances of four surface roughnesses, formed by mixing paint with different grit sizes, have been investigated using a flat plate friction plane and a rotating disk apparatus. The purpose of the experiments was to compare the results obtained with the plate and disk. An attempt was made to keep the roughnesses between the plate and disks of each plate-disk set identical but only with partial success. The plate and disk results were compared by first determining the boundary-layer similarity-law-roughness characterization ΔB from the measured resistances of the plates and torques of the rotating disks. The values of ΔB were then used to estimate typical full-scale friction drags as predicted from the plate and disk data. Taking into account the differences between roughness height measurements taken on the plates and disks, the compared extrapolated total friction drags for three of the four roughnesses were within 10 percent of each other. The results from the fourth and largest roughness show a larger disagreement between extrapolated values of total frictional drag. Except for Roughness 3, the discrepancies between measured changes in drag due to roughnesses on disks and plates were as much as 100 percent.

ADMINISTRATIVE INFORMATION

The work reported herein was supported by the Naval Sea Systems Command (PMS 393) under sponsor order number 9G002. The work was accomplished at the David W. Taylor Naval Ship R&D Center (DTNSRDC) under Task Area S0411001, Program Element 64561N and Work Unit 1508-902.

INTRODUCTION

In Reference 1, Granville presents methods by which arbitrary roughnesses can be characterized using data obtained from one of three apparatuses; the rotating disk, the friction plane, and the pipe. Of these three the rotating disk seems to be the most convenient and inexpensive to use and thus would be the preferred apparatus in most experiments. However, at this time there is little experimental data to confirm that these three methods will in fact produce the same roughness drag characterizations. The purpose of the present experiments was to characterize the drag of identical roughnesses using both the rotating disk and the friction plane.

The drag characteristics of four paint-grit mixtures have been investigated, the different surfaces representing varying degrees of roughness which might exist on full-scale ship hulls. The boundary-layer similarity-law-roughness characterization ΔB has been determined, using the methods of Reference 1, from the measured torque on the rotating disk and the measured drag on the friction plane. The values of ΔB obtained with the disk and friction plane are compared and used to predict full-scale ship friction coefficient values. These coefficients, taking into account the roughness height measurements on the plates and disks, are compared.

APPARATUS

FRICTION PLANE

The friction plane structure was installed in the 36-inch Variable Pressure Water Tunnel (VPWT) closed jet section. The surface plate consists of a fixed nose piece 27.9 inches (0.709 m) long, followed by a frame floating on flexures which restrain motion in the vertical and lateral directions. Motion in the longitudinal (flow) direction is restrained by a dynamometer which measures the drag. The actual test plates, 80 inches (2.03 m) long and 29.5 inches (0.749 m) wide and coated with the appropriate roughnesses, fit within the floating frame forming a continuous flat surface with the adjacent surfaces. Plates 24 inches (0.610 m) long and 29.5 inches (0.749 m) wide, with the same surface roughness characteristics as the test plates, fit into the nose piece.

ROTATING DISC

Measurements on 9-inch (0.229 m) diameter disks with surface characteristics corresponding to those of the plates were performed in a rotating disk apparatus described in Reference 2. Each disk was mounted on the end of a 1/2 inch diameter shaft in a 3.9 gallon (0.015 m^3) cylindrical housing. The shaft was rotated by a variable-speed (0-2200 rpm) 1-1/2 hp (1.12 X 10^3 W) DC motor. The torque was measured by a BLH Electronic Type "A" torque sensor and the sensor output was read using a digital voltmeter. The output readings were averaged over a ten second interval after steady state conditions were reached. The rotation rate was measured by a 60-tooth sensor.

DETERMINATION OF ΔB

The boundary-layer similarity-law-roughness characterization ΔB is used to compare the results from the plate and disk. The value of $(\Delta B)_e$ is determined as a function of roughness Reynolds number k^* from the gross measurements of drag of the plate or the torque of the rotating disk using methods developed by Granville.[1] The subscript e refers to conditions at the end of the plate or edge of the rotating disk. The Reynolds number k^* is defined as:

$$k^* = \frac{u_\tau k}{\nu}$$

where

u_τ - friction velocity, $\sqrt{\tau_o / \rho}$

τ_o - shear stress at wall

ρ - density of fluid

ν - kinematic velocity of fluid

k - roughness height

The values of $(\Delta B)_e$ are obtained from the following equations[1]

Plate

$$(\Delta B)_e = \left\{\left(\sqrt{\frac{2}{C_F}}\right)_r - \left(\sqrt{\frac{2}{C_F}}\right)_s\right\}_{(R_L C_F)_r = (R_L C_F)_s} \qquad [1]$$

Disk

$$(\Delta B)_e = 2.242 \left\{\left(\frac{1}{C_M}\right)_r - \left(\frac{1}{C_M}\right)_s\right\}_{(R_R C_M)_r = (R_R C_M)_s} + \frac{(\Delta B)'_e}{5} \qquad [2]$$

where

$C_F = D/(\frac{1}{2}\rho U_o^2 S)$ $\qquad R_L = U_o L/\nu$

$C_M = 2M/(\frac{1}{2}\rho\omega^2 R^5)$ and $\qquad R_R = \omega R^2/\nu$

and D - drag on plate

S - surface area of plate

U_o - freestream velocity over plate

$2M$ - moment developed on both sides of disk

R - radius of disk

$(\Delta B)_e'$ - $d(\Delta B)/d(\ln k^*)$

ω - angular velocity of disk

L - length of plate

The values of C_F and C_M are obtained from the measurements on the friction plane and the rotating disk respectively. The subscripts r and s refer to rough and smooth surfaces.

For the flat plate the value of k_e^* is given by

$$k_e^* = (u_\tau/U_o)_e R_L (k/L) \qquad [3]$$

and the corresponding local friction is given by

$$(u_\tau/U_o)_e = \sqrt{C_F/2}\,(1 - A\sqrt{C_F/2}) \qquad [4]$$

A has a value of 2.5 in the plate equations.

For the rotating disk the values of k_e^* are given by

$$k_e^* = (u_\tau/\omega R)_e R_R (k/R) \qquad [5]$$

and the corresponding local friction is given by

$$u_\tau/\omega R = 0.446(\sqrt{C_M})\left\{1 - \left[2A + (\Delta B)_e'\right]0.0892\sqrt{C_M}\right\} \qquad [6]$$

A has a value of 2.518 in the disk equations.

In order for values of $(\Delta B)_e$ determined from the plate and disc to be validly compared, the roughnesses on the plate and disc must be the same.

ROUGHNESS

The four roughnesses that were investigated consisted of paint-grit mixtures. They have been designated numbers 1 through 4 in order of increasing roughness. Each surface roughness was spray painted at the same time onto one plate and two disks. An effort was made to obtain identical rough surfaces on the plate and disks for each paint-grit mixture.

After the roughnesses were applied to the plates and disks, surface height measurements were made on all surfaces. A Clevite Brush Surfanalyzer was used to measure surface microroughness. On each plate twelve inch traverses were made laterally across the plate at eight different longitudinal locations. Four traverses were taken on each side of each disk. The traverses were taken along four chords at 90° to the adjacent chords. The maximum distance between each chord and its arc was 1 inch (2.54 cm). The locations of these traverses are illustrated in Figure 1.

The Surfanalyzer measures the arithmnetic average of the peak-to-trough roughness height given by

$$AA = \frac{1}{D}\int_{o}^{d} \left|k(x)\right| dx$$

where k(x) is the spatially varying surface trace and d is the length over which the measurement is taken. The value of d used in the measurements was 0.3 inches.

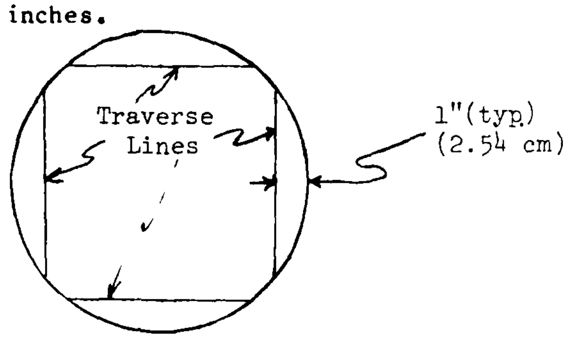

Figure 1 - Traverse Lines Used to Measure Roughness on the Disks

The results of the roughness measurements are given in Table 1. The table contains the mean values $\bar{k}$ and the ratios of the standard deviation σ to the mean. The values of $\bar{k}$ and σ were obtained using N roughness readings taken from the plate and the two disks designated A and B. Disk B of Roughness 3 was not used in the experiments because of defects in its painted surface. The results show that the plates were generally rougher than the disks. The exception is Roughness 3 where the disk was slightly rougher than the plate. The ratios $\sigma/\bar{k}$ also indicate that there are considerable differences in the roughness variations on the individual plates and disks.

RESULTS

The values of ΔB obtained with the disks and plates are plotted in Figures 2 through 5, for the four roughnesses, investigated as a function of k^*_e. The average value of roughnesses height $\bar{k}$, as given in Table 1,

TABLE 1 - ROUGHNESS READINGS TAKEN FOR PLATES AND DISKS

Roughness	Plates			Disks					
				A			B		
	N	$\bar{k}$	$\sigma/\bar{k}$	N	$\bar{k}$	$\sigma/\bar{k}$	N	$\bar{k}$	$\sigma/\bar{k}$
1	273	510 (0.0130)	0.118	97	448 (0.0114)	0.205	96	464 (0.0118)	0.185
2	263	760 (0.0193)	0.170	100	650 (0.0165)	0.098	95	634 (0.0161)	0.115
3	258	1943 (0.0493)	0.281	100	2057 (0.0522)	0.201	-	-	-
4	265	4846 (0.1230)	0.145	112	3624 (0.0920	0.233	104	3430 (0.0871)	0.182

$\bar{k}$ is in microinches (mm)

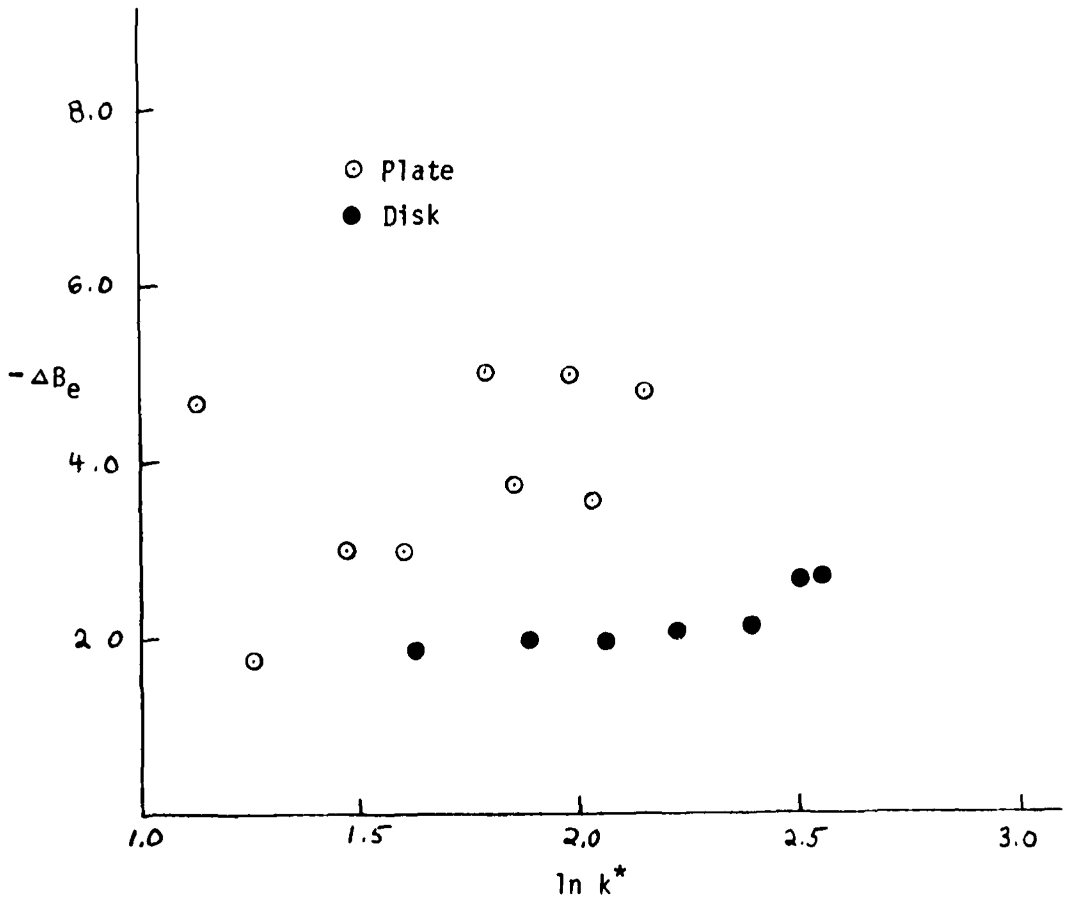

Figure 2 - Comparison of ΔB for Disks and Plate, Roughness Number 1

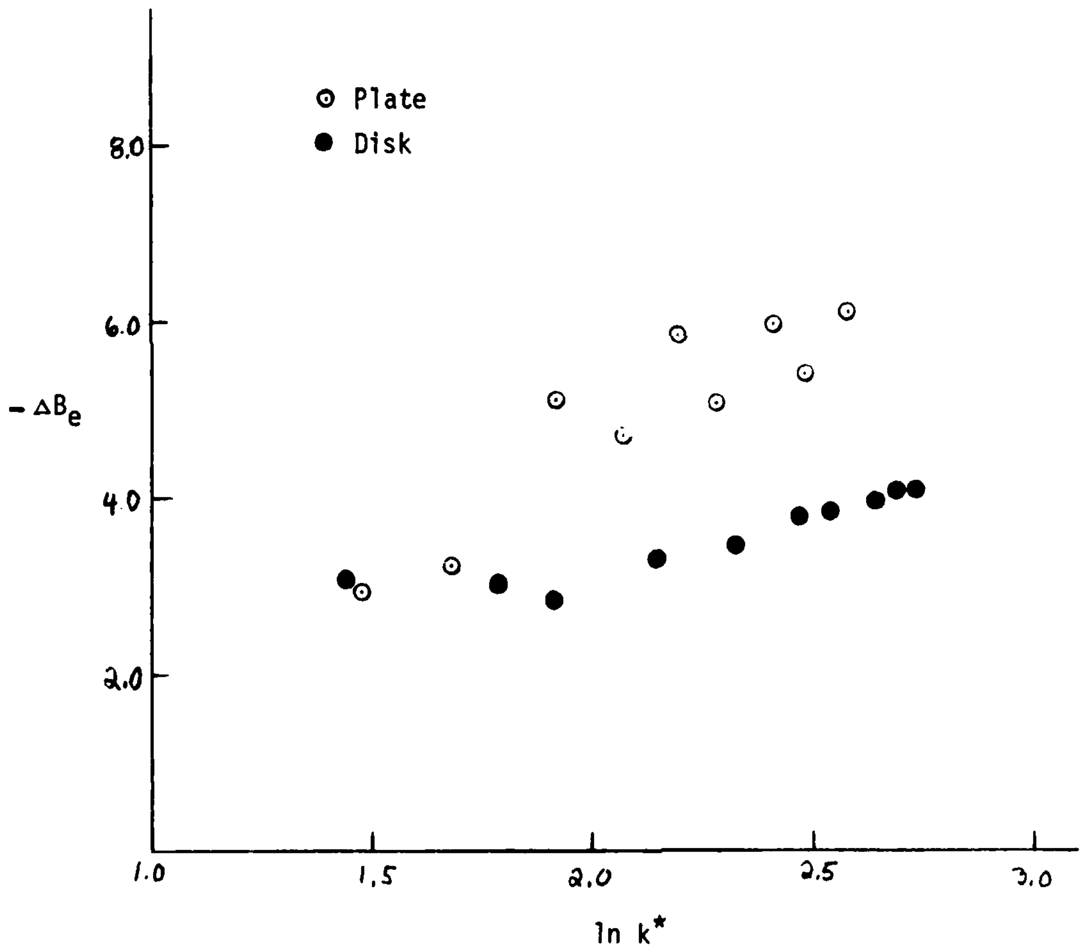

Figure 3 - Comparison of ΔB for Disks and Plate, Roughness Number 2

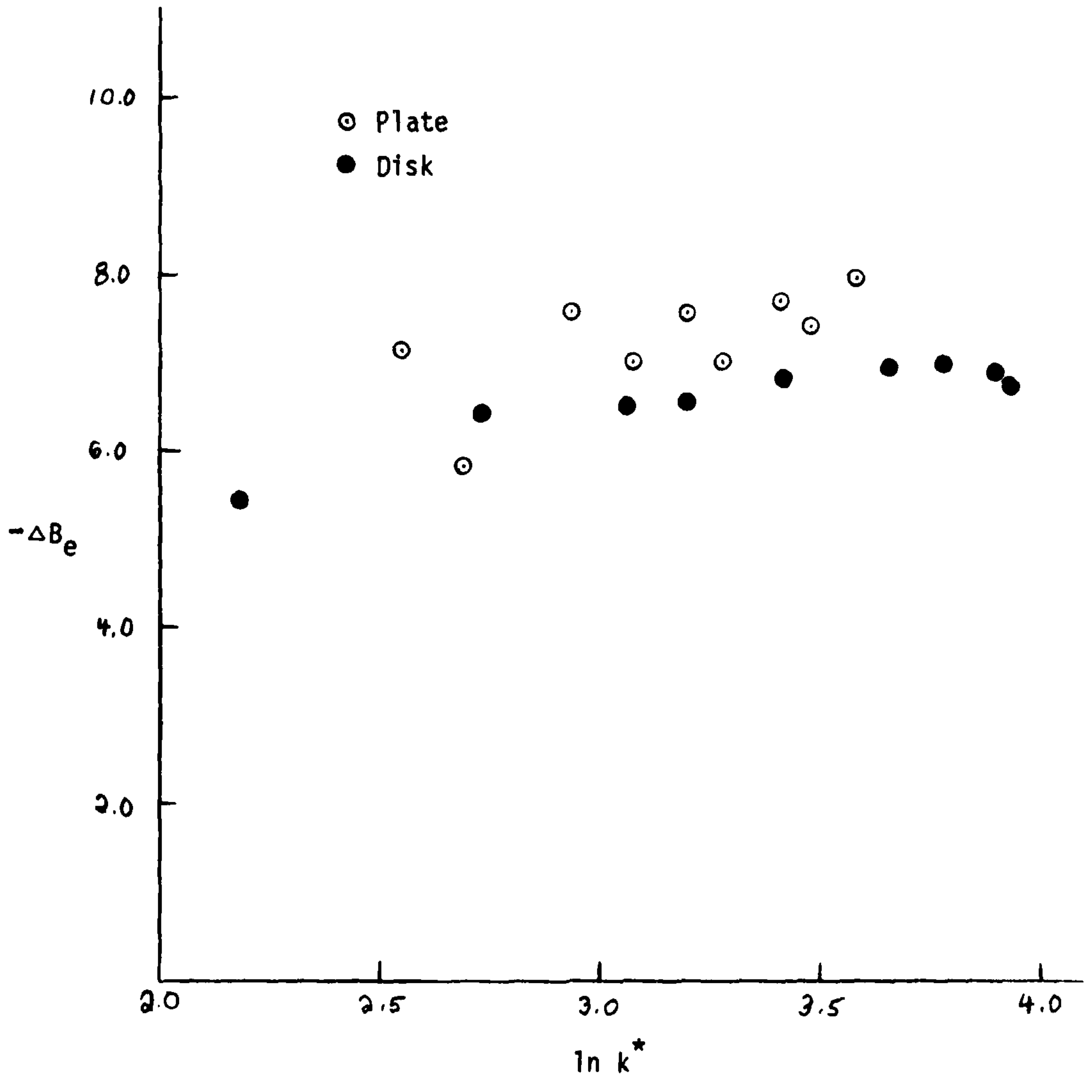

Figure 4 - Comparison of ΔB for Disks and Plate, Roughness Number 3

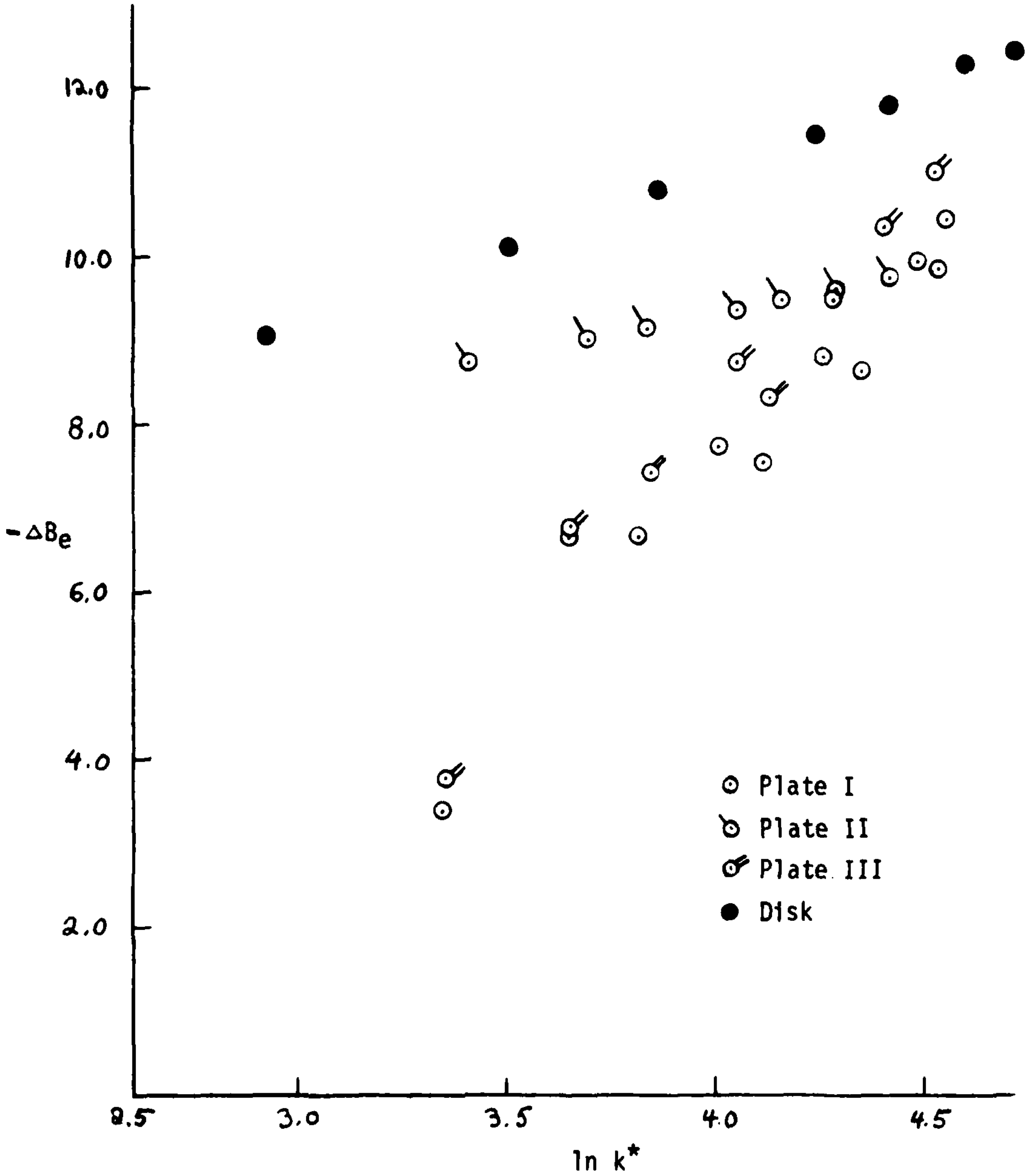

Figure 5 - Comparison of ΔB for Disks and Plate, Roughness number 4

was used to calculate k^*_e. Where two disks were used the average value of torque was used to obtain ΔB. The disk results have been corrected for the swirl that occurs when a rotating disk is operated in a closed container.[1] Three separate runs were made with the Roughness 4 plate as shown in Figure 5.

As shown in Figures 2 and 3, the ΔB's measured on Plates 1 and 2 indicate rougher surfaces than the ΔB's measured on Disks 1 and 2 respectively. This trend agrees with the trend of the roughness measurements given in Table 1 which indicate that Plate 1 has approximately a 10 percent larger roughness than Disk 1 and that Plate 2 has approximately a 15 percent larger roughness than the Disk 2.

Figure 4 shows close agreement between the ΔB's obtained with Plate 3 and Disk 3. There is also close agreement between the roughness measurements taken on this plate and disk as shown in Table 1.

The results obtained with Roughness 4 show ΔB's which indicate that the disk is rougher than the plate. This is the opposite of what is indicated by the roughness measurements where the plate was found to be approximately 27 percent rougher than the disk.

PREDICTION OF FULL SCALE DRAG

The roughness characterization ΔB has been determined as a function of a single dimensionless ratio k^* for a number of irregular roughnesses using the plate and the disk. To illustrate in a more practical way the significance of the results, values of ΔB and k^* are used to obtain flat plate friction lines $C_F(\log_{10}(R_L)_r, L/k)$ which are used to predict typical full scale friction drags. The method of converting ΔB to flat plate drag coefficients is outlined below and is given in more detail in Reference 1.

The value of $(C_F)_r$ as a function of $(R_L)_r$ is given by the intersection of two loci, one locus to satisfy ΔB and the other to satisfy k^*. The locus to satisfy ΔB is given by equation (7) which is valid at constant values of C_F

$$\log_{10} (R_L)_r = \log_{10}(R_L)_s - \frac{(\Delta B)_e}{2.3A} \tag{7}$$

For a constant value of $(\Delta B)_e$ the locus for the friction line with roughness is offset a constant amount in the direction of increasing $\log_{10} R_L$ from the smooth wall friction line for all values of C_F. The smooth wall friction line used in these calculations is given by equation (8).

$$(C_F)_s = \frac{0.0776}{(\log_{10} (R_L)_s - 1.88)^2} + \frac{60}{(R_L)_s} \tag{8}$$

The second locus which satisfies k^* is given by equation (9)

$$\log_{10}(R_L)_r = \log_{10}k^* + \log_{10}\sqrt{\frac{2}{C_F}} + \frac{A}{2.3}\sqrt{\frac{C_F}{2}} + \log \frac{L}{k} \tag{9}$$

For constant values of k^* and L equation (9) is plotted as a function of C_F. The value of k does not effect the computations and a dummy value of 1 inch (2.54 cm) was used. Also a constant flat plate length of L = 300 ft (91.4 m) was assumed.

The intersections of equations (7) and (9) give a point on the friction line $(C_F)_r$ for each ΔB - k^* combination. The friction lines obtained in this manner are shown in Figures 6 through 9. Three values of $\Delta B - k^*$ were used to construct the lines. These three values of $k^* - \Delta B$ are listed in Table 2 for both the plate and disks of all four roughnesses. Also listed are the friction coefficients $(C_F)_r$ and related Reynolds numbers $(R_L)_r$.

DISCUSSION

The differences in roughness between the plate and disks of each plate-disk set make direct comparison of plate-disk ΔB's and C_F values impossible. However some observations can be made by comparing differences in roughness measurements and in C_F values. When percentage differences in roughness heights and C_F values are cited it is not implied that there is a known relation between the arithmetic average height of roughness and the friction drag.

A summary of the comparison of the C_F values and roughness height measurements is given in Table 3. The results obtained with plate-disk Sets 1 through 3 seem to be qualitatively reasonable. For Sets 1 and 2 both the C_F values and the roughness measurements indicate the plates were rougher than the disks. While the C_F values for plate-disk Set 3 indicate a rougher disk; the differences are small. It is difficult to accurately estimate how equivalent the C_F values predicted from the plate and disk measurements are in characterizing the roughnesses since there is no way to quantitatively translate roughness height into drag. However, from the results given in Table 3, it is estimated

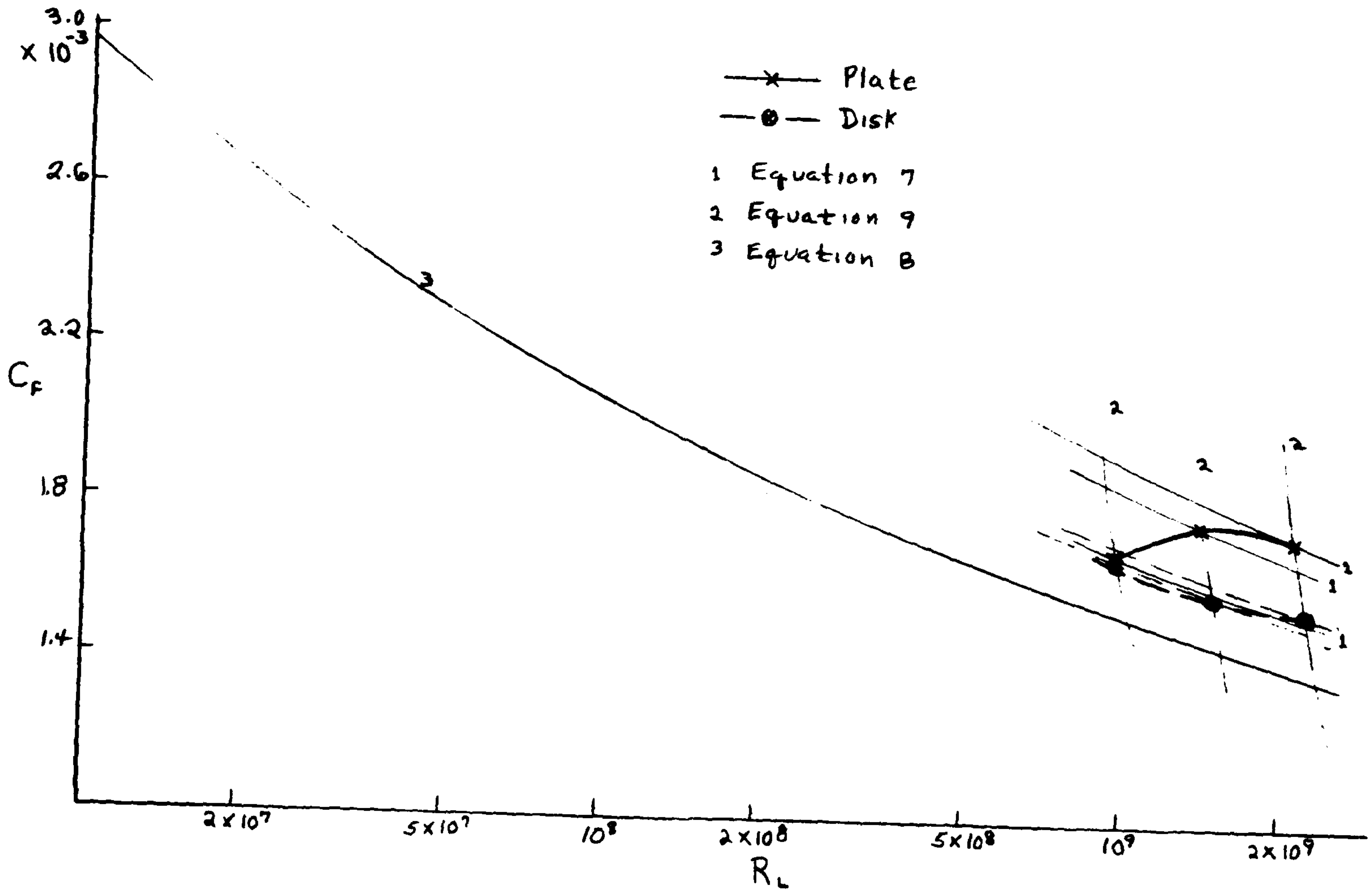

Figure 6 Flat Plate Roughness Diagram from ΔB Correlation - Roughness Number 1

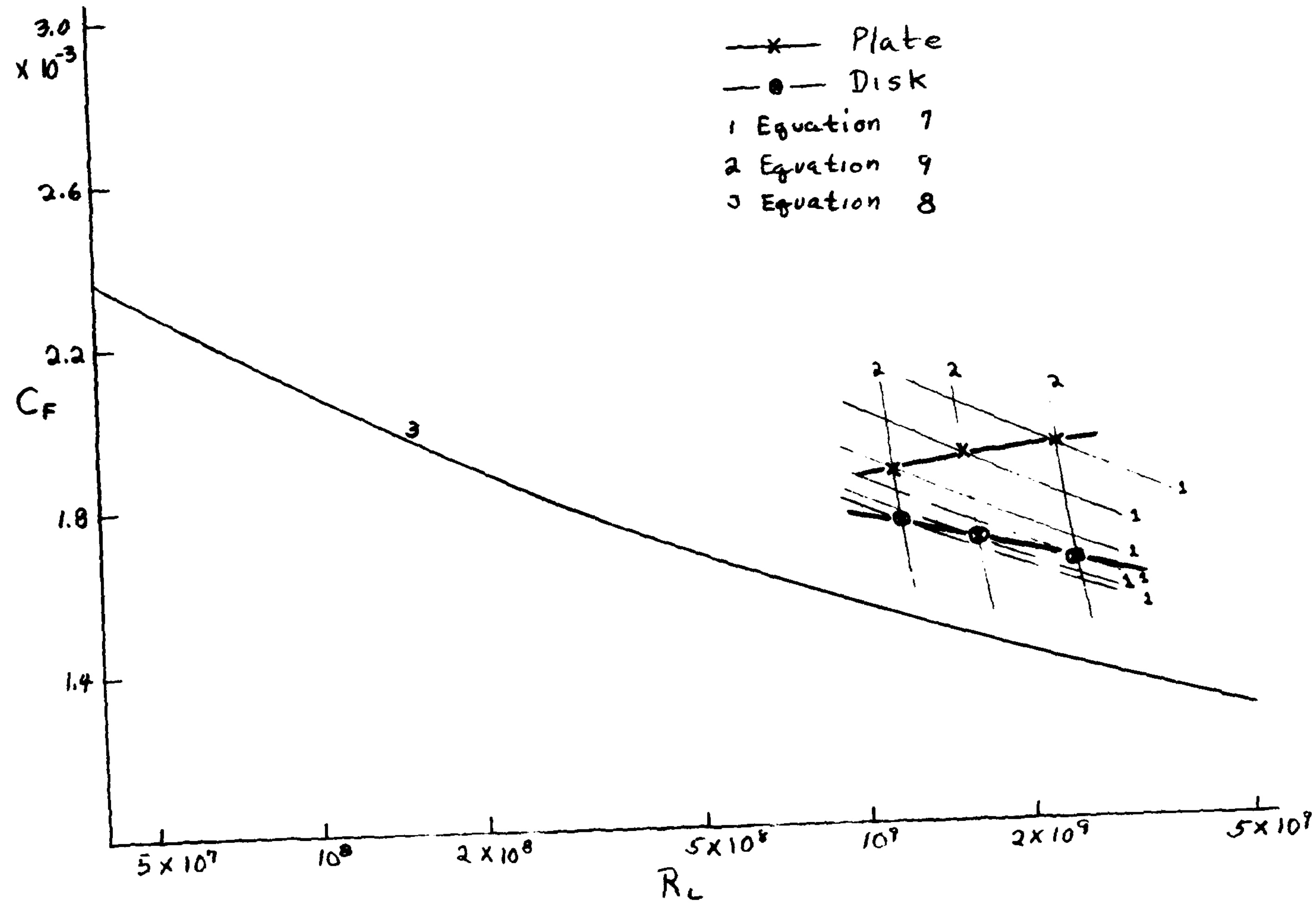

Figure 7 Flat Plate Roughness Diagram from ΔB Correlation - Roughness Number 2

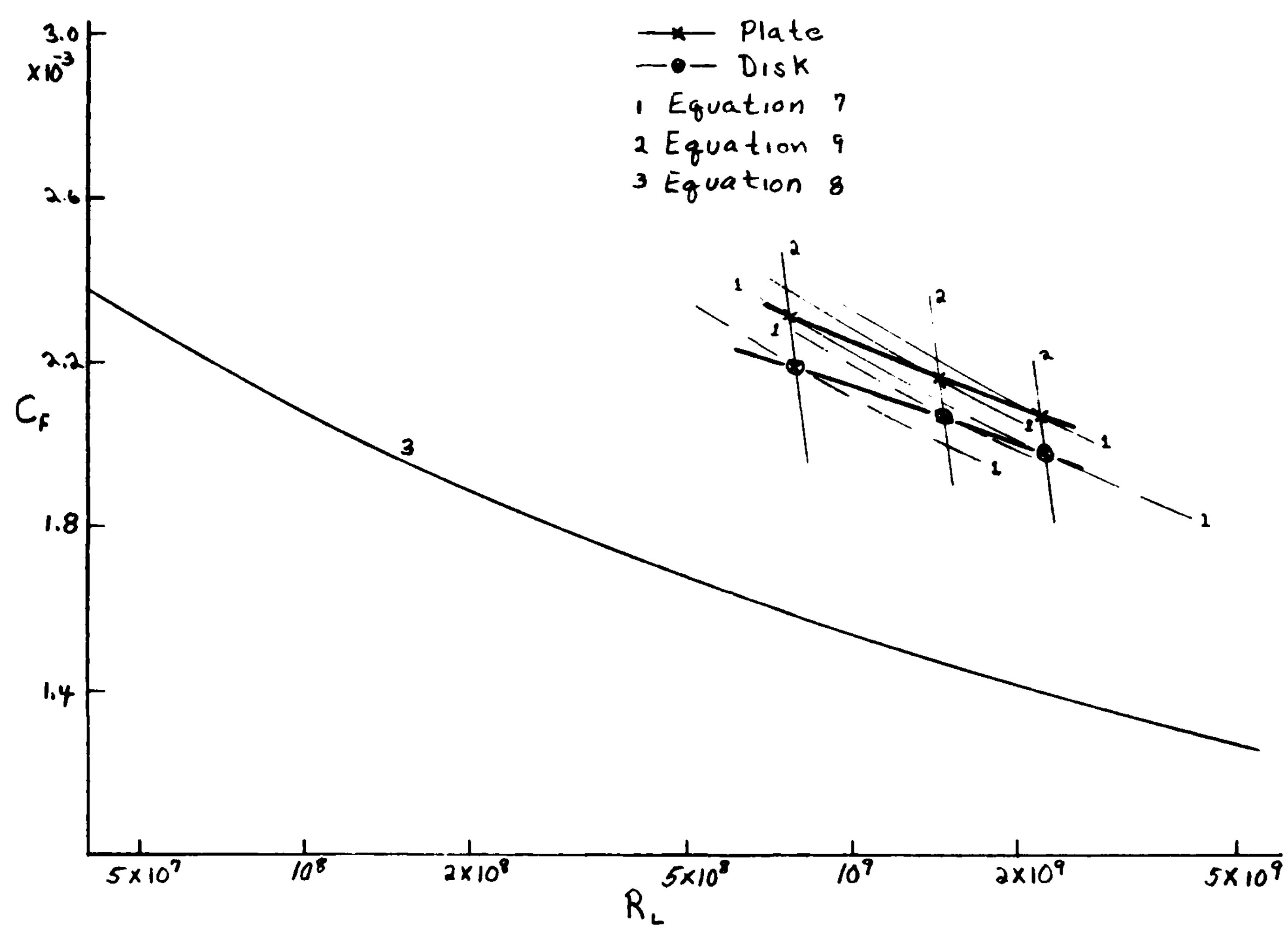

Figure 8 Flat Plate Roughness Diagram from ΔB Correlation - Roughness Number 3

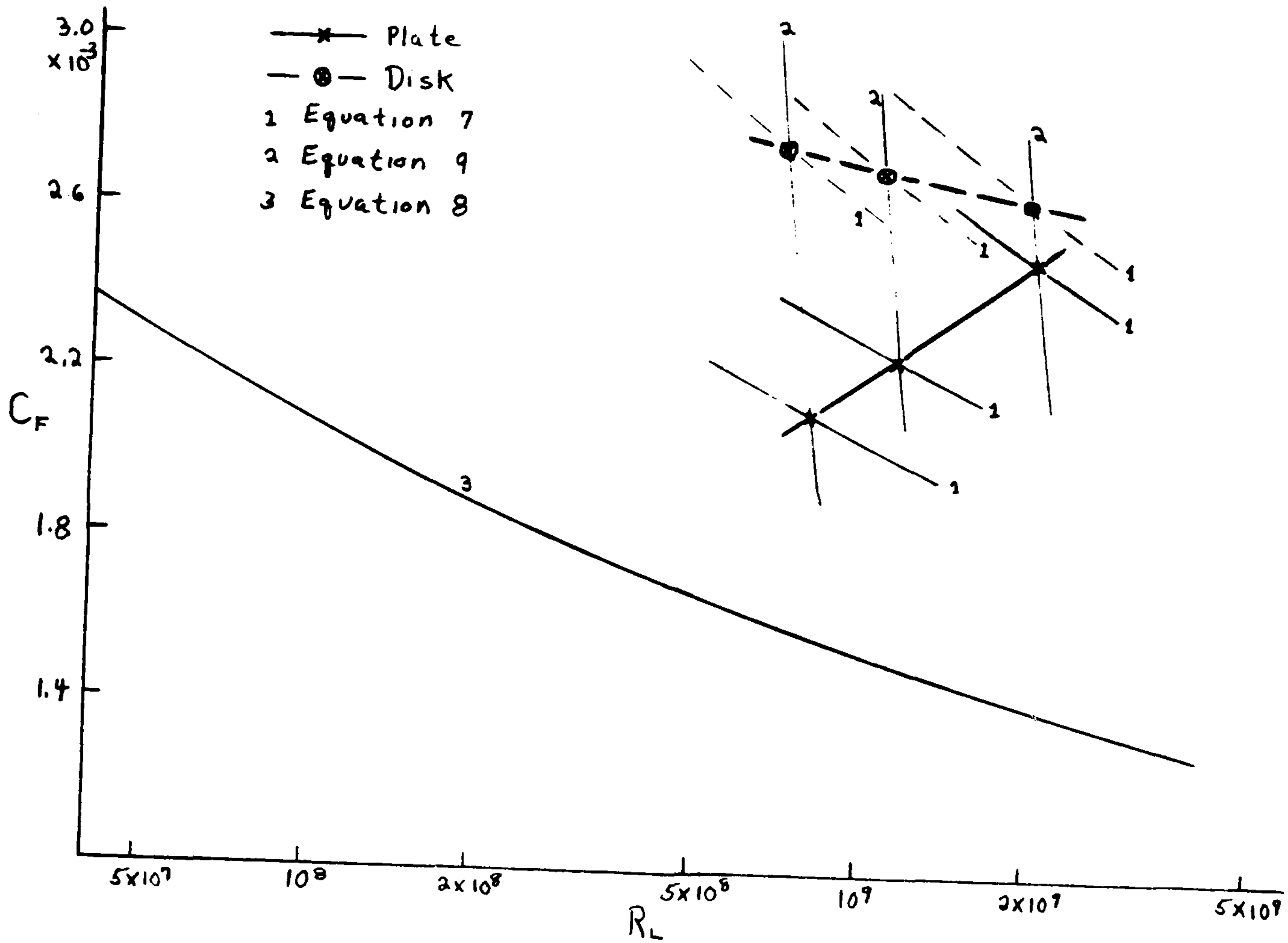

Figure 9 Flat Plate Roughness Diagram from ΔB Correlation - Roughness Number 4

TABLE 2 - FLAT PLATE FRICTION COEFFICIENTS FROM ΔB CORRELATION

Roughness	ln k*	ΔB		$(C_F)_\tau \times 10^3$		$(R_L)_\tau \times 10^{-8}$	
		Disk	Plate	Disk	Plate	Disk	Plate
1	8.9	-1.90	-2.00	1.68	1.69	9.8	9.7
	9.3	-1.90	-3.70	1.59	1.78	15.0	14.1
	9.7	-2.20	-4.40	1.55	1.74	22.7	21.4
2	9.0	-2.90	-4.10	1.73	1.86	11.8	11.4
	9.4	-3.10	-5.20	1.69	1.89	16.1	15.3
	9.8	-3.70	-5.80	1.64	1.92	24.3	22.6
3	8.8	-6.10	-6.40	2.19	2.31	7.9	7.7
	9.4	-6.70	-7.40	2.07	2.16	14.7	14.4
	9.8	-6.90	-7.70	1.98	2.07	22.3	21.9
4	8.8	-9.50	-5.49	2.75	2.11	7.0	8.0
	9.2	-10.20	-7.50	2.70	2.25	10.7	11.5
	9.8	-11.40	-10.55	2.63	2.49	19.5	20.0

TABLE 3 - COMPARISON OF C_F VALUES AND ROUGHNESS HEIGHT MEASUREMENTS

Roughness	Measurement	Remarks
1	C_F	Plate 0.6-12.5 percent more drag than disk
	$\bar{k}$	Plate 10 percent rougher than disk
2	C_F	Plate 7.5-17.1 percent more drag than disk
	$\bar{k}$	Plate 15 percent rougher than disk
3	C_F	Plate 4.3-5.4 percent more drag than disk
	$\bar{k}$	Disk 5 percent rougher than plate
4	C_F	Disk 5.6-30.0 percent more drag than plate
	$\bar{k}$	Plate 27.0 percent rougher than disk

that the plate and disk gave results within 10 percent of each other for plate-disk sets 1 through 3 when $(C_F)_r$ is used as a measure.

In contrast to these results, the results obtained with plate-disk Set 4 show poor agreement; the disk C_F values are 5.6 to 30 percent higher than the plate values while the roughness measurements indicate that the plate is 27 percent rougher than the disk. The reason for these large discrepancies between the plate and disk results is not known. Possible sources of error are discussed below.

For the plate experiments the gap between the test plate frame and the adjacent fixed structure could cause an increase in friction drag and create pressure drag due to the pressure gradient along the test section causing a pressure differential between the forward and rear faces of the frame. Small misalignments of the plate surface with the adjacent surfaces could also contribute to increasing drag. Because care was taken to keep any misalignment to a minimum, the effect of alignment errors should not be sufficient to cause the discrepancy between plate and disk results obtained with Roughness Number 4.

Several disturbing factors which cannot be explained were noted in the plate experiment results. A very large tare drag was obtained using an hydraulically smooth plate. The tare drag significantly effects the result obtained. It was measured twice during the experiments without change in results. The measured drag of the painted plate was corrected by subtracting the tare drag. Also it can be seen from Figures 6, 7 and 9 that the value of C_F increases with increasing R_L for three of the four roughnesses. The expected results for a constant value of L/k would be decreasing or constant values of C_F. In addition there was a large amount of scatter in the plate results for all four roughnesses as can be seen in Figures 2 through 5.

In contrast the results obtained with the rotating disk show much less scatter and the computed values of C_F decrease with increasing values of R_L for all roughnesses. A possible source of error in the rotating disk experiments is the effect of container size on measured torque. Although the results were corrected for the effect of container size there is some doubt about the accuracy of the correction. Additional sources of error could be the effect of the disk edge including grit that accumulated on the edge.

CONCLUSIONS

The drags of four surface roughnesses have been characterized using both a friction plane and a rotating disk apparatus. Ideally the roughnesses applied to the plate and disks of each plate-disk set were to have been identical. In practice, the average roughness heights of the plate and disks as measured by a stylus type instrument, were as much as 27 percent different. This difference made a direct comparison of plate-disk results, using the boundary-layer similarity-law-roughness characterization ΔB, impossible. However the results from the friction plane and disk were compared using typical full-scale values of C_F obtained from the plate and disk experiments and the roughness measurements. The values of C_F were determined from friction lines constructed from the measured roughness characterization ΔB and the Reynolds number k*. For Roughnesses 1 through 3 the total friction drag values of the disk and plate were estimated to be less than 10 percent different from each other. For Roughness 4 the results showed greater disagreement. Except for Roughness 3, the discrepancies between measured changes in drag due to roughnesses on disks and plates were as much as 100- percent.

Despite the partial agreement between the friction drag predictions derived from the plate and disk data it is recommended that these experiments be repeated with the following changes:

1. Use sand grains and screens as roughnesses. These roughnesses can be reproduced more accurately than the paint-grit mixtures thus assuring a more similar roughness on the plate and disk. In addition experiments with at least one painted surface should be repeated.

2. Install pressure taps on the forward and aft faces of the sample plate frame to determine the magnitude of any pressure differences. Determine if the pressure differences are sensitive to small changes in the frame orientation.

3. Conduct experiments with the rotating disk in different size containers to determine the effect of container size on disk measurements.

4. Experimentally determine the effect of disk edge roughness on measured value of torque.

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